

THE WEPP MODEL FOR RUNOFF AND EROSION PREDICTION UNDER SPRINKLER IRRIGATION

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ABSTRACT. *Potential runoff and erosion is a serious problem for some types of sprinkler irrigation systems, particularly traveling laterals and center pivots on medium- to heavy-textured soils operating on sloping land. Prediction of when runoff might occur is part of the system design process. The USDA-ARS Water Erosion Prediction Project (WEPP) model was tested with 3 years of field data under high-rate sprinklers in southern Idaho. Runoff and soil loss were measured on the upper, middle, and lower portions of a hillslope. The main parameter affecting infiltration and runoff was the effective hydraulic conductivity. Model predictions for average runoff and soil loss were improved when hydraulic conductivity values were adjusted to account for soil variability across the field. Runoff amounts were small, and prediction variability for individual furrows was quite high, but no more than would be expected from previous studies of infiltration variability. Soil loss predictions were unreliable for the small runoff amounts occurring in this study. The most reasonable use of WEPP for sprinkler irrigation would be for estimating when potential runoff might occur under center pivots for different soils, slopes, and crop management practices, and to determine limits on application depths and rates to avoid serious runoff.*

Keywords. *Sprinkler irrigation, Infiltration, Runoff, Erosion, WEPP.*

The USDA-ARS Water Erosion Prediction Project (Flanagan and Nearing, 1995; Flanagan and Livingston, 1995) model was developed to predict runoff and erosion primarily on rain-fed cropland and rangeland. Laflen et al. (1991) and Nearing et al. (1989) describe the model and its processes. An irrigation component (furrow and sprinkler) was added to the 1995 version to extend its range of possible application. Bjorneberg et al. (1999) evaluated WEPP for furrow irrigation and found problems due to the inherent differences between furrow flow and rainfall runoff. Sprinkler irrigation, however, is similar to rainfall in most respects. The sprinkler irrigation component allows users to input irrigation amount and application rate for specified days, or to specify an irrigation schedule based on soil water depletion level. An additional user input allows modification of the effective sprinkler droplet impact energy as it affects interrill soil detachment. Since WEPP was designed to simulate uniform rainfall, the irrigation component can simulate constant application rate sprinkler irrigation over an entire hillslope, such as solid-set systems or stationary individual laterals placed parallel to the slope. Extending its use to traveling laterals is discussed herein.

Sprinkler irrigation is characterized by distributing water as discrete droplets through the air, and thus is similar to natural rainfall. However, WEPP rainfall is assumed to be

applied over an entire field simultaneously, whereas irrigation may be applied to a small portion of a field at varying intensities.

The irrigation designer has control over the amount, intensity, areal extent, and timing of water application, as influenced by water supply and economic, soil, and crop considerations. The most important factor with regard to sprinkler erosion potential is the average application rate within the wetted area at any given time. The application rate is inversely proportional to the wetted area for a given total flow rate. The type of sprinkler system most similar to rainfall is the solid-set system, with a grid of stationary sprinklers operating simultaneously, covering a specified area with a relatively uniform, low-intensity application. Solid-set sprinklers are well suited to low intake rate soils and steep slopes, and they rarely have problems with runoff. Moveable stationary laterals are similar but usually have higher intensities.

At the other end of the spectrum are continuously moving laterals. Because of the high cost per unit length, traveling laterals irrigate a large area and have high discharge rates and high instantaneous application rates. Potential for runoff is common on medium- to heavy-textured soils, and erosion potential is significant with these systems on steeper slopes. Due to the ease of operation and low labor requirements, traveling laterals and center-pivot laterals are becoming the system of choice for new installations and conversions from surface irrigation systems. Approximately one-half of the 25 million hectares of irrigated land in the U.S. is now irrigated by sprinkler, and about two-thirds of this area is under center-pivot irrigation (Irrigation Journal, 2000). Center pivots are often used on variable topography and medium-textured, erodible soils.

A center pivot is a traveling lateral that pivots about one end, irrigating a circular area. Due to their popularity, it is worthwhile to describe their characteristics in more detail.

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The system capacity (often expressed in mm/day or gpm/acre) and the length of the lateral determine the discharge rate, which increases in direct proportion to the distance from the pivot. Thus, the greatest potential for runoff occurs near the outer edge of the field. Pivot laterals are commonly 400 m (1/4 mi) in length and irrigate about 52 ha (130 acres). The type of sprinkler used on the lateral also affects the application rates, which are inversely proportional to the width of the sprinkler pattern. Lower pressure sprinklers are increasingly popular, and these have reduced pattern widths, although they may produce smaller droplets. Sprinkler droplet sizes are affected by the nozzle pressure, nozzle size, and sprinkler type. Large drops have large impact energy on the soil, producing splash erosion, and this in turn affects infiltration rates and runoff. Kincaid et al. (1969) used a simple empirical infiltration model to estimate potential runoff amounts from center pivots, and thus aid in design and management of these systems. WEPP contains a more sophisticated infiltration model and predicts the effects of cropping system and tillage on infiltration rates. The primary objective here was to determine whether WEPP could be used as a tool to predict potential runoff under sprinkler irrigation. A secondary objective was to evaluate the WEPP erosion predictions if runoff occurs.

Although WEPP was not designed to handle traveling-storm runoff, the model might reasonably apply to center pivots where the lateral is parallel to the slope so that the entire hillslope receives water simultaneously at a relatively high rate, or very short (probably less than a span length) but steep hillslopes where the slope is watered in a short time. The use of WEPP for center-pivot irrigation should be limited to estimating potential runoff on hillslopes where the runoff direction runs nearly parallel to the lateral. This is a worst-case scenario for center-pivot irrigation, since runoff tends to concentrate and create erosive concentrated flows.

MODEL PROCESSES AND PARAMETERS

WEPP was designed for continuous simulation of the hydrologic process using a daily time step, and it can handle only one rainfall or irrigation event per day. Input data files must be constructed describing the climate, slope, soil properties, crop management, and irrigation. The hillslope can be divided into several sections (overland flow elements, or OFEs) that can have different soil properties and management practices. The WEPP watershed model combines several hillslopes to form a watershed and routes runoff through a series of concentrated flow channels.

The most important component of modeling runoff and erosion is predicting infiltration and rainfall excess. The WEPP hillslope model calculates infiltration using the Green-Ampt model as described by Mein and Larson (1973). The main parameters in this model are the effective hydraulic conductivity, soil water deficit, and wetting front suction. Soil water is calculated in the model by a daily water balance of applied water and evapotranspiration. The wetting front suction is calculated internally and is not user-controllable. The key parameter that the user can alter is the effective hydraulic conductivity, which may be held constant or allowed to vary. For the constant case, the user inputs an average value (K_e) representing all soil conditions. For the variable case, the user inputs a "baseline" value (K_b), which

is an initial high value representing conditions after tillage on a fallow soil. The model will then decrease K_b to account for management practices. If the user has no initial estimate for K_b , then the model will calculate a value based on soil texture alone, which for soils with <40% clay content is:

$$K_b = -0.265 + 0.0086 \text{ SAND}^{1.8} + 11.46/\text{CEC}^{0.75} \quad (1)$$

and for soils with >40% clay:

$$K_b = 0.0066 \exp(244/\text{CLAY}) \quad (2)$$

where SAND and CLAY are percent sand and clay, respectively, and CEC is cation exchange capacity of the soil.

The random roughness of the soil surface can have a significant effect on runoff. Rainfall excess is reduced before runoff begins by depression storage, or water ponded on the surface, which eventually infiltrates. The maximum or available depression storage, S_d (m), is computed by (Onstad, 1984):

$$S_d = 0.112 r_r + 3.1 r_r^2 - 1.2 r_r S_0 \quad (3)$$

where r_r is the random roughness (m), and S_0 is the surface slope (m/m). The random roughness is set to a maximum value on the day of tillage (dependent on the type of tillage) and is reduced approximately 20% for each succeeding rainfall or sprinkler irrigation event until a minimum value of 0.006 m is reached. Typical suggested values for random roughness are: moldboard plowing = 0.043 m, disking = 0.026 m, and cultivating = 0.015 m. The final tillage operation before the irrigations simulated here was a cultivation/corrugation operation with $r_r = 0.015$ m. In trial runs, doubling this value reduced average runoff by 10% to 15%.

Surface runoff is modeled using a simplified kinematic wave procedure (Woolhiser and Liggett, 1967). The rill width (0.15 m used here) and spacing (1.1 m) are the only user-adjustable hydraulic parameters, and the model was found to be relatively insensitive to these parameters. The model predicts the amount and duration of runoff and peak runoff rate, which are then used in the hillslope interrill and rill erosion component. The main parameters in the erosion model are the interrill erodibility, rill erodibility, and critical shear. The model provides suggested values for each soil type. Interrill erosion is soil detached by rainfall and delivered to rills, where it is transported downslope. Rill erosion is soil detachment, transport, and deposition within a rill. Detachment occurs when shear in the rill exceeds critical shear. Deposition occurs whenever the sediment load exceeds the transport capacity (Foster et al., 1981; Foster, 1982).

EXPERIMENTAL PROCEDURES

Field experiments were conducted on the University of Idaho Research and Extension Center farm near Kimberly in southern Idaho during the 1984 to 1986 irrigation seasons. The field was near the area used for WEPP rainfall simulation tests used to establish soil erodibility but had steeper slopes than did the WEPP site. A 120 m long hillslope was irrigated using a stationary portable lateral sprinkler system on a previously furrow-irrigated field. The soil was Portneuf silt loam (coarse-silty, mixed, superactive, mesic Durinodic Xeric Haplocalcids), which had a bulk density of about

1.35 g/cm³. The soil water holding capacity is 32% by volume at field capacity and 14% at wilting point. The crop was dry beans, planted in 0.56 m rows running downslope with small furrows (rills) on 1.12 m spacing. The hillslope was divided into three equal-length OFEs of about 40 m each. The average slope was 1.5%, 3.8%, and 2.6% on the upper, middle, and lower OFEs, respectively (listed as OFE 1, 2, and 3 in table 4). Runoff rates from each OFE were measured with small flumes placed in the furrows. Sediment samples (1 L) were collected from each flume at approximately 10-minute intervals. Sediment concentration was determined by filtering. Sediment samples were not collected for some tests (table 1).

A single sprinkler lateral was placed parallel to the slope so that each furrow received a nearly constant irrigation rainfall rate. Two types of sprinklers were used: single nozzle part-circle impact sprinklers, which produced application rates up to 25 mm/hr, and spray heads, which gave rates up to about 50 mm/hr. The droplet kinetic energy for the impact sprinklers and spray heads was about 15 J/kg and 8 J/kg, respectively (Kincaid, 1996). Each test applied water to a group of 10 to 20 furrows, and data were collected from a total of 48 furrows. Application rates for individual furrows and OFEs were measured with catch cans placed between furrows. Antecedent soil water in the upper 150 mm was measured gravimetrically prior to each test. All irrigations were measured for each group of furrows for an irrigation season. Furrow groupings changed for some tests because of the type of sprinkler used and the overall pattern width. Some furrows received more irrigations and more total water than others, resulting in a wide variation in irrigation depths and rates among individual furrows.

MODEL SIMULATIONS

The most recent public version of the WEPP model, version 99.5, was used in these simulations. The model was

run using a 4- or 6-year continuous simulation, the first 3 years being a hypothetical cropping and irrigation scenario to set up the soil management parameters. The remaining one- or 3-year period simulated the actual fixed-date irrigations that were measured (furrows 17-48 were only measured for one year). Daily weather data for Kimberly were used in the 6-year climate file.

Input files were constructed for running the simulation as either a single OFE or as a 3-OFE hillslope. Although each furrow was run as a separate simulation (i.e., a separate irrigation file), the furrow runs were combined into three groups of approximately equal size to determine how the model would predict runoff and soil loss for different sets of data, and how soil properties might vary across the field as well as downslope. Furrow group 1-16 contained three years of data, while the other groups had only one year of data. Comparisons were made between measured and model-predicted total runoff, peak runoff rate, soil loss, and volumetric soil water content. The WEPP User Manual (Flanagan and Livingston, 1995) was consulted for suggested values of the soil parameters listed in table 2.

MODEL PREDICTIONS

Simulations were run with the hillslope defined as either one or three OFEs. If the soil parameters were set to the same values in each of the three OFEs, then the model gave the same overall runoff and soil loss from the slope with one or three OFEs. The use of three OFEs with different K values did not significantly improve the predictions, as will be seen. Results for simulations using a single OFE are listed in table 3, using a range of constant or variable K values. Measured and model-predicted runoff, peak rate, and soil loss were averaged for all runs within each furrow group, and root mean squared runoff prediction error (RMSE) was calculated for each group. Various K values were tried in an

Table 1. Sprinkler runoff test summary.

Year	Date	Test No.	Sprinkler type	Furrows	Duration (hrs)	Sediment samples
1984	6/20	1	Impact	2-17	3	yes
	6/22	2	Spray	17-33	2	yes
	6/26	3	Spray	32-47	2	yes
	7/19	4	Spray	32-47	2.2	yes
	7/26	5	Impact	1-14	2.7	yes
	7/31	6	Impact	1-17	2	yes
	8/08	7	Impact	30-42	2.5	yes
	8/08	8	Impact	41-48	2.3	yes
	8/14	9	Impact	27-38	2.2	no
	8/15	10	Impact	12-24	2.3	yes
	8/21	11	Impact	1-11	3	no
1985	7/17	1	Impact	1-6	1.5	yes
	7/19	2	Impact	9-16	3	yes
	7/25	3	Impact	9-16	1.5	no
	8/07	4	Impact	3-5	3	yes
	8/13	5	Impact	9-15	3	yes
1986	7/22	1	Impact	1-6	3.2	no
	7/25	2	Impact	1-6	2.8	no
	7/29	3	Impact	7-12	2.8	no
	8/07	4	Impact	1-6	2.7	no
	8/13	5	Impact	7-12	3.2	no
	8/25	6	Impact	1-6	2.7	no

Table 2. Soil properties and effective hydraulic conductivity values for Portneuf silt loam.

Sand content, %	19.5
Clay content, %	11.1
Organic matter content, %	1.2
CEC, meq/100g	12.6
Constant K_e , mm/hr	2.5
Variable (baseline) K_b , mm/hr ^[a]	3.3
Simulator measured K_e , mm/hr	7.9
Interrill erodibility, kg-s/m ⁴	5442060
Rill erodibility, s/m	0.0215
Critical shear, N/m ²	3.5

[a] Calculated by equation 1.

attempt to minimize RMSE. The standard constant K value for this soil is about 3 mm/hr. For furrows 1–16 with a constant $K_e = 3.3$ mm/hr, the average model predictions were close to measured values, but when using a variable K it was necessary to increase K_b to 6 mm/hr to minimize RMSE. For the two other furrow groups, it was necessary to considerably increase the K values to bring predicted runoff to near measured levels. This shows the sensitivity of the model runoff predictions to the conductivity value. For the variable case, the average model-computed conductivity is approximately 60% of the initial or baseline value. There was no apparent advantage in prediction accuracy when using variable K.

Results from the 3–OFE simulations using constant K are shown in table 4, which gives average measured and predicted runoff and the optimized K_e values for the three groups of furrows and for all furrows combined. The value of K_e for each OFE was adjusted by trial and error until the

model-predicted average runoff volume approximated the average measured runoff, and RMSE was minimized. The model tended to overpredict runoff on OFE 3, so K_e values were increased for downslope OFEs. Optimum results over all furrows were obtained with a K_e value of about 3 mm/hr on the upper OFE and about 5 mm/hr on the lower OFE. This indicated that effective K_e varied both across the field as well as downslope.

For furrows 1–16, where the most data were available, the average soil loss predictions were good, but the overall RMSE for soil loss was high (0.15 kg/m²). Average predicted soil loss was higher than measured values for the other two furrow groups. The overall RMSE for soil loss for all 48 furrows was 0.7 kg/m². The data showed a few extremely high predicted values for soil loss, which greatly increased the average. These are events where runoff was considerably overpredicted, and an example of this is given in table 5. With the K_e values from table 4, predicted runoff for this event was two to three times higher than measured, and soil loss was five to ten times higher than measured. When the K_e values were increased to bring runoff near to measured levels, soil loss values were reasonably close to those measured. Adjustments in the interrill and rill erodibility parameters were tried (corresponding to doubling the soil clay content), but these had relatively little effect on soil loss compared to changing K_e . This shows the extreme sensitivity of the model results to the soil effective conductivity parameter.

The soil water results are not shown, but model-predicted soil water prior to each irrigation was usually within 2% by volume of the measured soil water in the top 0.3 m. This indicates that the water balance computations performed adequately.

Table 3. Model-predicted (P) and measured (M) runoff, peak runoff rate, and erosion with constant or variable K and single OFE hillslope.

Furrow group	K_e, K_b (mm/hr)	Mrun (mm)	Prun (mm)	RMSE (mm)	Mpk (mm/hr)	Ppk (mm/hr)	Msl (kg/m ²)	Psl (kg/m ²)
1–16	3.3	5.4	5.6	5.6	6.4	5.6	0.053	0.080
	4.0	5.4	3.0	5.7	6.4	3.6	0.053	0.049
	3.3	5.4	12.5	11.5	6.4	9.3	0.053	0.195
	5.0	5.4	6.5	8.2	6.4	6.1	0.053	0.078
	6.0	5.4	4.1	7.8	6.4	4.5	0.053	0.041
	7.0	5.4	2.3	7.9	6.4	2.9	0.053	0.018
	8.0	5.4	1.3	7.9	6.4	1.8	0.053	0.008
17–34	4.5	5.0	5.5	5.5	4.9	5.9	0.048	0.182
	5.0	5.0	4.4	5.0	4.9	4.6	0.048	0.157
	6.0	5.0	3.1	4.8	4.9	3.4	0.048	0.132
	6.0	5.0	7.9	7.3	4.9	8.2	0.048	0.151
	7.0	5.0	5.7	6.2	4.9	6.7	0.048	0.116
	8.0	5.0	3.8	5.9	4.9	5.1	0.048	0.065
	8.5	5.0	3.0	5.8	4.9	4.3	0.048	0.046
35–48	5.0	4.1	10.1	11.8	5.3	9.0	0.015	0.488
	7.0	4.1	6.2	7.6	5.3	6.6	0.015	0.255
	8.0	4.1	4.7	6.5	5.3	5.4	0.015	0.171
	9.0	4.1	3.5	5.8	5.3	4.3	0.015	0.104
	8.0	4.1	10.4	11.1	5.3	9.4	0.015	0.462
	12.0	4.1	5.2	6.6	5.3	5.5	0.015	0.220
	14.0	4.1	4.3	5.8	5.3	5.7	0.015	0.181
	16.0	4.1	3.6	5.5	5.3	5.4	0.015	0.142

Mrun, Mpk, and Msl = Measured runoff, peak runoff rate, and soil loss, respectively.

Prun, Ppk, and Psl = Model-predicted runoff, peak runoff rate, and soil loss, respectively.

RMSE = Total root mean square error in runoff prediction.

K = soil water effective conductivity (mm/hr).

OFE = Overland flow element.

Table 4. Measured and model-predicted runoff, peak rate, and soil loss with 3 OFE hillslope.

Furrow group	OFE No.	Obs No.	K_e (mm/hr)	Mrun (mm)	Prun (mm)	RMSE (mm)	Mpk (mm/hr)	Ppk (mm/hr)	Msl (kg/m ²)	Psl (kg/m ²)
1-16	1	115	2.9	7.8	7.7	8.3	8.0	10.8	0.041	0.042
	2	115	3.7	5.9	5.9	5.9	6.9	6.9	0.170	0.051
	3	115	3.6	5.4	5.1	5.6	6.4	5.4	0.053	0.045
17-34	1	44	3.4	8.7	8.8	7.0	8.4	15.0	0.023	0.139
	2	44	5.1	6.5	6.3	5.7	6.4	8.5	0.231	0.516
	3	44	5.1	5.0	5.1	5.5	4.9	5.2	0.048	0.254
35-48	1	40	7.0	7.7	6.2	8.3	9.2	17.1	0.017	0.174
	2	40	11.0	6.0	3.6	6.2	6.9	8.8	0.126	0.510
	3	40	13.0	4.1	2.6	6.0	5.3	5.1	0.015	0.172
1-48	1	199	3.5	8.0	7.9	9.5	8.3	12.5	0.031	0.141
	2	199	4.7	6.0	5.9	7.7	6.8	7.3	0.175	0.512
	3	199	4.8	5.1	4.9	8.1	5.9	5.0	0.043	0.271

Mrun, Mpk, and Msl = Measured runoff, peak runoff rate, and soil loss, respectively.

Prun, Ppk, and Psl = Model-predicted runoff, peak runoff rate, and soil loss, respectively.

RMSE = Root mean squared error for runoff.

Table 5. A single-event case study for furrow 28, day 174, 1984.

K_e (mm/hr)			Erodibility		OFE	Runoff (mm)			Soil loss (kg/m ²)		
OFE 1	OFE 2	OFE 3	Interrill (kg-s/m ⁴)	Rill (s/m)		1	2	3	1	2	3
					Measured	11.3	12.7	10.1	0.02	0.87	0.17
3.4	5.1	5.1	5442060	0.0215	Predicted	32.9	28.5	26.9	0.67	2.99	1.27
3.4	5.1	5.1	4897850	0.0215	Predicted	32.9	28.5	26.9	0.61	2.97	1.26
3.4	5.1	5.1	4897850	0.00855	Predicted	32.9	28.5	26.9	0.60	1.86	1.20
5.0	7.0	7.0	5442060	0.0215	Predicted	24.5	20.3	18.8	0.49	1.84	0.87
7.0	9.0	9.0	5442060	0.0215	Predicted	15.9	12.7	11.5	0.32	0.76	0.52
9.0	9.0	9.0	5442060	0.0215	Predicted	9.3	9.4	9.4	0.19	0.21	0.21

DISCUSSION

These results represent a less demanding use of the model than might be expected under typical conditions where optimized K_e values are not available. The model adequately predicted overall average runoff when K_e values were adjusted upward from the baseline values given in the WEPP User Manual. WEPP can predict runoff reasonably well under sprinkler irrigation if the effective soil conductivity values can be estimated by experience for soils in a given area. However, the prediction variability is quite high, as evidenced by the high values of RMSE relative to average values.

There was no tendency for better runoff prediction on the upper or lower OFEs. The upper end of the field apparently had reduced infiltration capacity (resulting in higher runoff) compared to the lower end, due perhaps to previous erosion and deposition from furrow irrigation. The runoff, peak rate, and soil loss predictions for furrows 1-16 were reasonably accurate when using K values close to the manual-suggested values. There was a tendency for overprediction of peak runoff rate and soil loss on field areas where the infiltration rates (and optimized K_e values) were higher than normal (e.g., furrows 17-48). This tendency was exaggerated when much higher K_e values were used on the lower OFE to optimize predicted runoff. This causes the model to predict a short runoff duration, which is used over the entire slope, resulting in high peak runoff rates on upper OFEs. Thus, when using multiple OFEs, it is better not to use widely different K values.

To put the high runoff prediction variability in perspective, consider the normal field variability of infiltration.

Trout and Mackey (1988) found that the average furrow infiltration coefficient of variation (CV) in southern Idaho was 25%. Viera et al. (1981) calculated the CV of 1280 ring infiltrometer measurements taken on a field grid as 40%. When most of the applied water infiltrates, the field average rainfall excess is often less than the normal infiltration variability. For example, if measured runoff is 10% of the applied depth (the approximate amounts seen here), then a 10% error in predicting infiltration amount could easily result in a 100% error in predicting runoff. In addition, error in measuring the average application rate is typically about 5%. It is, therefore, unreasonable to expect the model, using field-average K values, to precisely predict small runoff amounts for individual furrows.

As discussed above, the predicted erosion is highly sensitive to the runoff rate, and the erosion prediction error is two or three times higher than the runoff error. The high variability of soil loss predictions makes the use of this model for erosion prediction questionable for small runoff amounts.

CONSIDERATIONS FOR MODELING RUNOFF FROM CENTER-PIVOT IRRIGATION

Sprinkler systems, and particularly center pivots, often operate on complex topography. The slope direction relative to the lateral affects how runoff can accumulate and cause erosion. If the lateral is perpendicular to the slope direction, then runoff will tend to move away from the lateral, reducing the tendency for concentrated flow and thus reducing the surface travel distance before infiltration. However, if the slope is parallel to the lateral, then runoff can accumulate

downslope and may result in erosive concentrated flows. If crop ridges are present, the row direction relative to the slope and lateral also affects the runoff flow direction. It is common practice to ridge row crops perpendicular to a traveling lateral or in a circular pattern under a pivot to help direct runoff away from the lateral. The wheel tracks themselves (about 40 m apart) provide runoff-intercepting channels, further complicating the process. If the lateral is traveling upslope, runoff will move onto a previously wetted area, whereas with downslope travel, runoff can move onto dry soil. Thus, a complete runoff-erosion model for center-pivot sprinkler systems must be able to handle both the rainfall-runoff situation and furrow-rill flow with infiltration or any combination thereof.

The slope can be divided into several OFEs, but since wheeltracks often intercept runoff flows, it is probably best to run the model with short hillslopes in single-OFE mode. For cases where the slope is perpendicular to the lateral, the model may still be used with some reservations. The upper portion of the slope where no run-on occurs may be handled normally. The effective application rate could be adjusted to account for partial-area rainfall. Since wheeltracks often become concentrated flow channels, which disrupt the normal runoff direction, the overall slope could be divided into smaller span-length (30–50 m) hillslopes and combined in the WEPP watershed model. These scenarios and limitations need to be explored further.

In summary, the model tended to overpredict runoff using the suggested soil conductivity values, and conductivity can vary within a field, for example between eroded and non-eroded areas. WEPP can be used as an irrigation design and management tool to help prevent runoff. With good management, the potential for serious erosion under sprinkler irrigation is small. The continuous simulation process can be used to study the effect of different crop and soil management scenarios on potential runoff under center-pivot irrigation.

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REFERENCES

- Bjorneberg, D. L., T. J. Trout, R. E. Sojka, and J. K. Aase. 1999. Evaluating WEPP-predicted infiltration, runoff, and soil erosion for furrow irrigation. *Trans. ASAE* 42(6): 1733–1741.
- Flanagan, D. C., and M. A. Nearing, eds. 1995. USDA Water Erosion Prediction Project: Technical Documentation. NSERL Report No. 10. West Lafayette, Ind.: USDA-ARS-NSERL.
- Flanagan, D. C., and S. J. Livingston, eds. 1995. USDA Water Erosion Prediction Project: WEPP User Summary. NSERL Report No. 11. West Lafayette, Ind.: USDA-ARS-NSERL.
- Foster, G. R. 1982. Chapter 8: Modeling the erosion process. In *Hydrologic Modeling of Small Watersheds*, 297–360. ASAE Monograph No. 5. C. T. Haan, ed. St. Joseph, Mich.: ASAE.
- Foster, G. R., L. J. Lane, J. D. Nowlin, J. M. Laflen, and R. A. Young. 1981. Estimating erosion and sediment yield on field-sized areas. *Trans. ASAE* 24(5): 1253–1262.
- Irrigation Journal*. 2000. 50(1), 16–31. Arlington Heights, Ill.: Adams Business Media.
- Kincaid, D. C. 1996. Spraydrop kinetic energy from irrigation sprinklers. *Trans. ASAE* 39(3): 847–853.
- Kincaid, D. C., D. F. Heermann, and E. G. Kruse. 1969. Application rates and runoff in center-pivot sprinkler irrigation. *Trans. ASAE* 12(6): 790–797.
- Laflen, J. M., L. J. Lane, and G. R. Foster. 1991. WEPP: A new generation of erosion prediction technology. *J. Soil Water Cons.* 46(1): 34–38.
- Mein, R. G., and C. L. Larson. 1973. Modeling infiltration during a steady rain. *Water Resources Research* 9(2): 384–394.
- Nearing, M. A., G. R. Foster, L. J. Lane, and S. C. Finkner. 1989. A process-based soil erosion model for USDA: Water Erosion Prediction Project technology. *Trans. ASAE* 32(5): 1587–1593.
- Onstad, C. A. 1984. Depression storage on tilled soil surfaces. *Trans. ASAE* 27(3): 729–732.
- Trout, T. J., and B. E. Mackey. 1988. Furrow inflow and infiltration variability. *Trans. ASAE* 31(2): 531–537.
- Viera, S. R., D. R. Nielsen, and J. W. Biggar. 1981. Spatial variability of field-measured infiltration rate. *Soil Sci. Soc. Am. J.* 45(6): 1040–1048.
- Woolhiser, D. A., and J. A. Liggett. 1967. Unsteady, one-dimensional flow over a plane: The rising hydrograph. *Water Resources Research* 3(3): 753–771.